09/936775

Rec'd PCT/PTO 17 SEP 2001

WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high-optical-confinement waveguide structure and a method for forming the same.

Background of the Invention

High-confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 a wavelength of about 1.5 μm. High confinement optical waveguides based on silicon as the waveguide core material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique, oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the

complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The step of forming the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner which forms a ridge structure in the deposited waveguide layer. The method may further comprise a step of depositing a second layer of a second material so as to form an etch-stop, whereby to enable the formation of the ridge structure. Accordingly, the height of the ridge structure can be more

accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise a step of creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer. The step of creating the refractive index variation may comprise exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

The waveguide layer may further comprise a dopant material.

The deposited waveguide layer may further comprise at least partially-oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The waveguide may be deposited by plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may further comprise forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre. The step of forming the waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide. The step of creating the variation of the refractive index in the end portion may comprise carrying out controlled oxidation of the end portion. The controlled oxidation may comprise using a

laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise a step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as an optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising: - oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at a wavelength of 1.5 μm) to that of silicon dioxide (1.46 at wavelength of 1.5 μm) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement

optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by high temperature processing, such as rapid thermal annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment,

small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling losses are high due to an optical mode mismatch between silica (fibre) and silicon systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical mode of the fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.